Weather Note

ISENTROPIC UPSLOPE MOTION AND AN INSTANCE OF HEAVY RAIN OVER SOUTHERN FLORIDA

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ABSTRACT

During October 12–15, 1965, the southern part of Florida received an unusually heavy and prolonged rainstorm. Although the conventional isobaric analyses did not reveal any obvious pre-existing disturbance which would be expected to produce such a result, isentropic charts suggest that intense convection was being initiated and sustained by an organized lift of conditionally unstable air to saturation. Accompanying the heavy rainfall was the formation in the lower troposphere during the 14th of a tropical depression which is thought to have been of convective origin.

1. INTRODUCTION

Between the 12th and the 15th of October 1965, a rainstorm of unusually prolonged duration and high intensity struck southern Florida and its surrounding waters. The storm was especially noteworthy for having produced very heavy rainfall in the area between Miami and Palm Beach (fig. 1). Radar and ship reports indicate that the precipitation may have been as heavy over the Florida Straits and the contiguous Atlantic waters. Near Ft. Lauderdale most of the precipitation fell during the first 18 hr. on the 14th. Elsewhere over the southern and central portions of the State the total rainfall was considerably lighter, but still appreciable.

Isolated showers were reported over the Florida Straits on the 11th and on the following day heavy showers were observed near Key West. Throughout the next three days the rainfall continued to intensify as the entire pattern of radar echoes shifted slowly east-northeastward. Echo tops, as seen by the U.S. Weather Bureau 10-cm. radar in Miami, were as high as 35,000–40,000 ft. on the 12th. By the 15th maximum radar tops were observed at 40,000–50,000 ft. but by that time the rainfall had abated over the peninsula. The tallest echoes during the 14th and 15th were located mainly over the ocean to the southeast of Ft. Lauderdale except between the hours of 0900 and 1200 GMT on the 14th when tops of 40,000 ft. were observed over land in that area.

Excessively rainy outbreaks are probably not very uncommon in the subtropics but such occurrences at any given population center are rather infrequent. On occasion there is a preference for the heaviest amounts of rain to be concentrated along the coast between Miami and Palm Beach. This tends to be reflected in mean maps of Florida rainfall. Sourbeer and Gentry [1] have described a somewhat similar situation which occurred on January 21, 1957. Then, over 21 in. of rainfall were recorded not far from Ft. Lauderdale. Again on October 31, 1965, falls of 14–20 in. were measured in the vicinity of Ft. Lauderdale. In both of these instances the rainfall was not produced by a few isolated cumulonimbi, but was

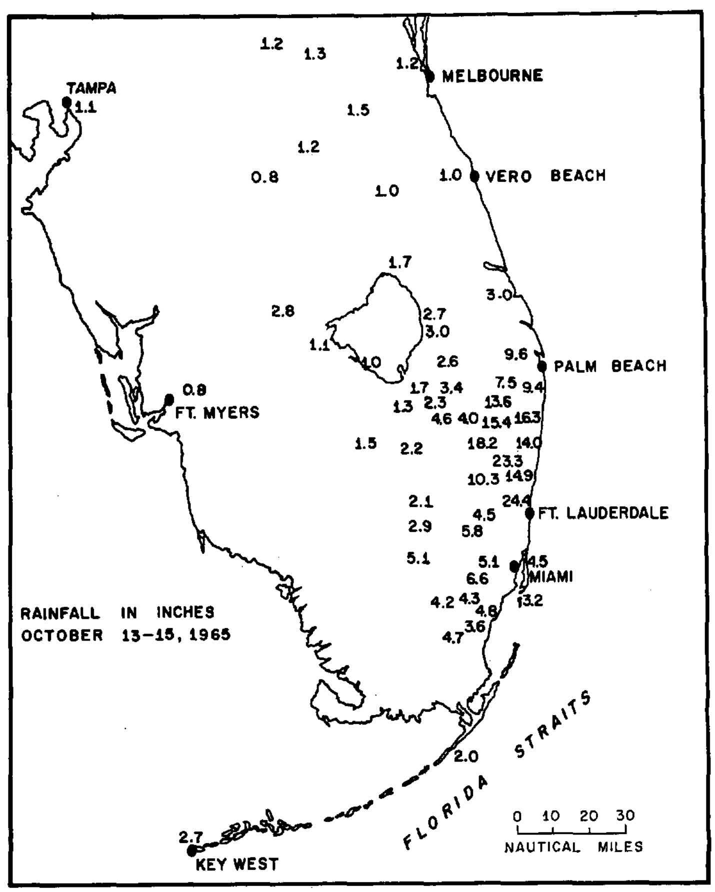

FIGURE 1.—Map of lower Florida showing 3-day rainfall totals in inches for October 13–15, 1965. (Supplementary rainfall measurements courtesy of U.S. Army Corps of Engineers, Jacksonville, Fla.)

part of a more general pattern, one not readily apparent from an examination of the conventional charts. Less spectacular, but still very appreciable and widespread rainstorms affect southern Florida, particularly during the spring and autumn months. Many of these situations are not associated directly with fronts or other commonly recognized pre-existing disturbances, and are often difficult to predict by means of standard isobaric and frontal models. Nevertheless, the extensive nature of the rainfall and cloud patterns suggests a systematic organization on a large scale.

2. GENERAL DESCRIPTION

Isobaric charts at 500 mb. (fig. 2) and 1000 mb. (fig. 3) at 0000 GMT on the 14th were characterized by a small-amplitude trough and ridge system which had been moving eastward at a speed of about 9 kt. The zone of cloudiness associated with this system extended from middle latitudes into the subtropics and had been moving eastward at a speed of 9–12 kt. in the north and 5–6 kt. south of latitude 30° N. The low-level easterly flow over the region, as it is on many occasions (both dry and rainy), is shown to be rather strong and unperturbed, and even weakly anticyclonic north of the Florida Straits. Yet, despite the apparently unperturbed pattern presented by these charts, lower Florida and the Florida Straits had been experiencing heavy rainfall for more than 24 hr. prior to map time.

The streamlines and isobars, drawn from surface data (figs. 4 and 5), show that the low-level flow became increasingly cyclonic and confluent in the area of heavy precipitation, and by the 15th a distinct vortex and cut-off center in the surface pressure field (lowest pressure 1011 mb.) formed near the site of the heaviest rainfall (fig. 6). The vortex was confined entirely to the lower 500 mb., although a circulation of sorts was observed in the 700–850-mb. layer somewhat to the northeast of Key West on the 14th. As the tropical depression continued to move eastward during the 16th (see fig. 6), the winds some distance north of the center increased to about 40 kt. In some respects this situation resembles the early stages of a tropical storm formation described by Frank [2]. During the course of the 3-day rainstorm the middle troposphere warmed both at Miami and Grand Bahama; the magnitude of the warming is shown by comparison of the Key West sounding with that of Miami (fig. 7). The anomalously high temperatures between 400 and 700 mb. in the vicinity of the most intense convection suggest that the warming was produced by the mixing of convective updrafts with the environment rather than by advection.

Much of the precipitation fell as heavy rain from cumulonimbi but an appreciable amount also fell either as showers or as sustained rain from a higher-based convection which appeared to be indistinguishable from the middle-cloud system. Aircraft reconnaissance observations show that the middle cloud was broken to overcast, and layered. Embedded in this cloud system were

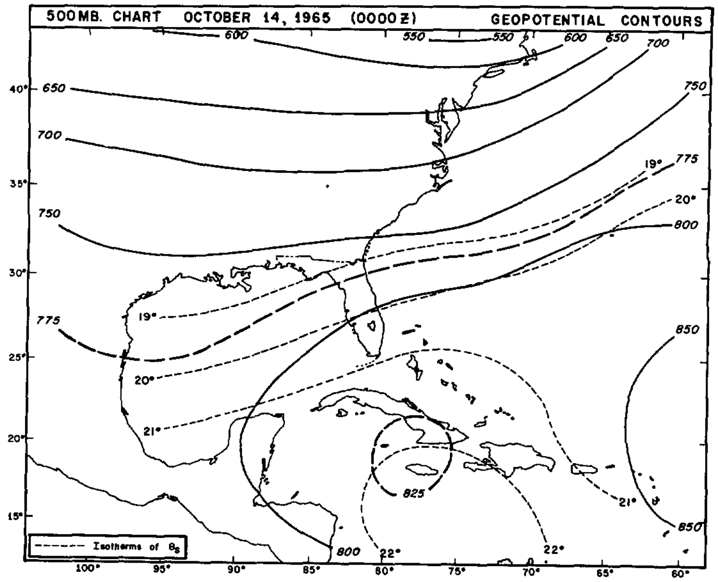

FIGURE 2.—Contours of the 500-mb. surface (continuous and heavy dashed lines) labeled in meters above 5,000, and isotherms of saturation wet-bulb potential temperature θ_s (thin dashed lines) labeled in °C., 0000 GMT, October 14, 1965.

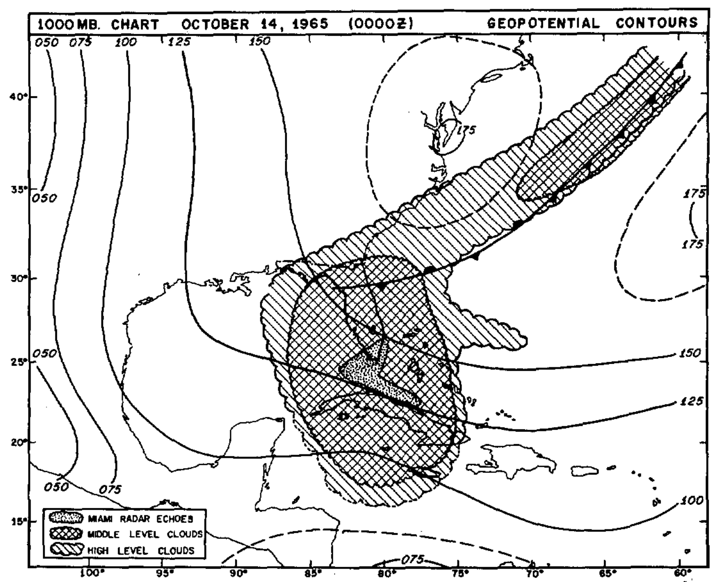

FIGURE 3.—Contours of the 1000-mb. surface (continuous and dashed lines) labeled in meters, and standard frontal analysis, 0000 GMT, October 14, 1965. Hatched and crosshatched areas represent cover of middle and high cloud, respectively. Stippled area represents the primary echoes as seen by radar at Miami, Fla.

numerous buildups of convective towers to 15,000–18,000 ft. which were growing from bases at 6,000–10,000 ft. In some places there was little low cloud apparent during the showers from the higher cloud. As shown in figure 5, the base of this middle cloud was lowest in the vicinity of the most intense convection (below 7,500 ft.). Where it was not obscured by the presence of lower cloud and heavy rain, the middle cloud was reported either as altostratus or altocumulus (type 2 or 7 in the standard surface weather code).

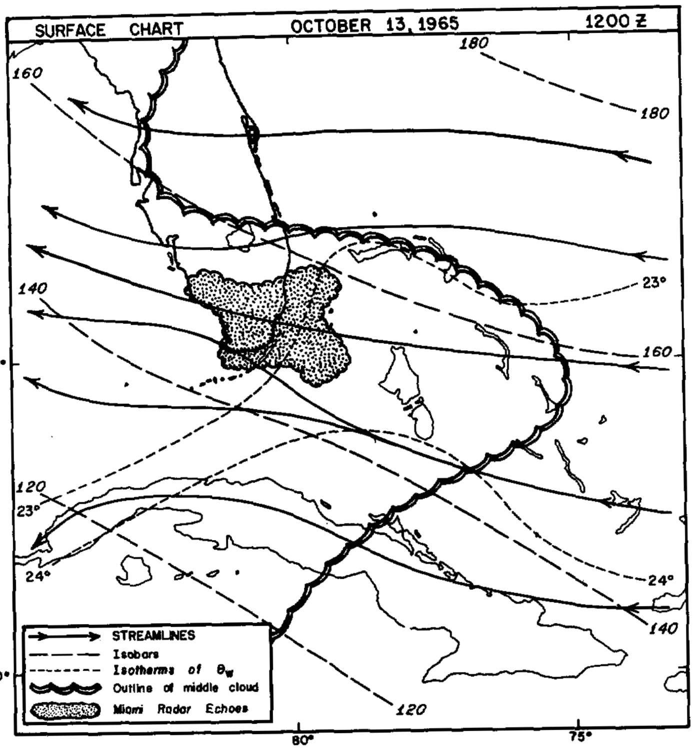

Figure 4.—Surface streamlines (solid lines), isobars (heavy dashed lines) labeled in millibars and tenths above 1000, and isotherms of wet-bulb potential temperature θ_w (thin dashed lines) labeled in °C., 1200 GMT, October 13, 1965. Scalloped border represents outline of middle cloud cover, and stippled area the primary echoes as seen by radar at Miami, Fla.

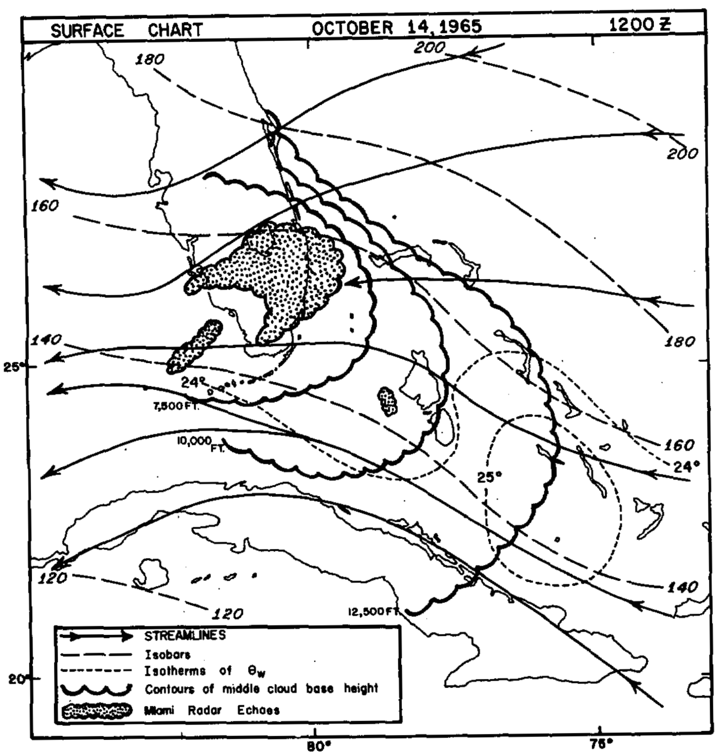

Figure 5.—Surface streamlines (solid lines), isobars (heavy dashed lines) labeled in millibars and tenths above 1000, and isotherms of wet-bulb potential temperature θ_w (thin dashed lines) labeled in °C., 1200 GMT, October 14, 1965. Scalloped lines represent contours of middle cloud base height labeled in feet. The 12,500-ft. contour corresponds closely to the edge of the middle cloud cover. Stippled area represents the primary echoes.

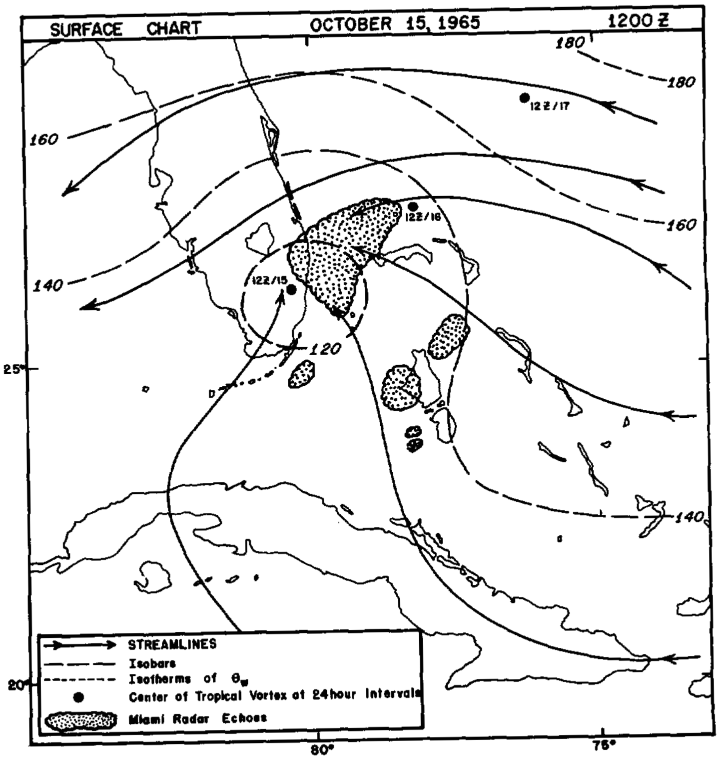

Figure 6.—Surface streamlines (solid lines) and isobars (heavy dashed lines) labeled in millibars and tenths above 1000, 1200 GMT, October 15, 1965. Stippled areas represent the primary echoes. Solid circles show positions of center of tropical depression at 24-hr. intervals from map time until 1200 GMT on the 17th.

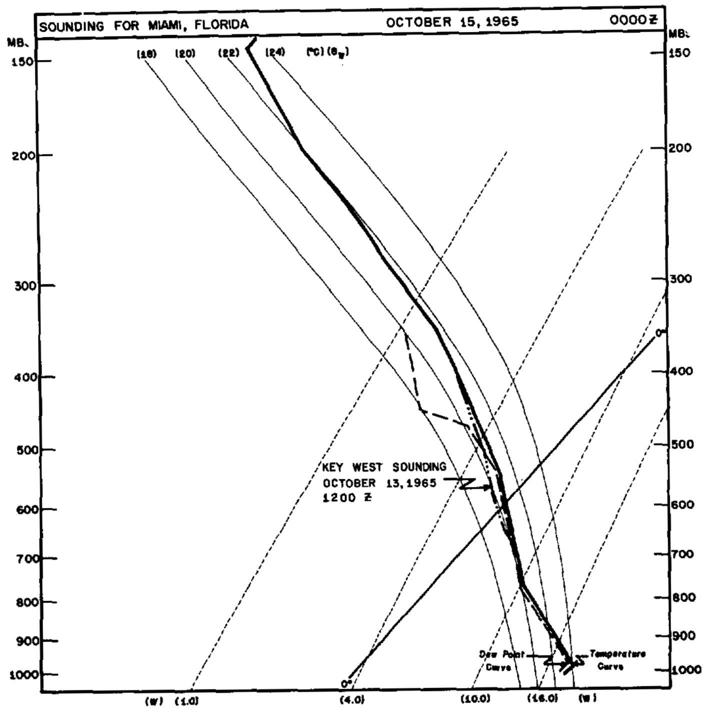

Figure 7.—Sounding for Miami, Fla. (station 72202), 0000 GMT, October 15, 1965, as shown on a skew T-log p diagram. In this and subsequent soundings wet adiabats are labeled in wet-bulb potential temperature θ_w in °C. The dashed lines are for saturation mixing ratios, w, of 1, 4, 10, and 16 gm./kgm.; 0°C. isotherm is drawn as solid line. The temperature ascent is shown as solid curve and dew point distribution by a heavy dashed curve. Part of the sounding for Key West, Fla. (station 72201), 1200 GMT, October 13, 1965, is entered in the diagram as a dash-dotted curve.

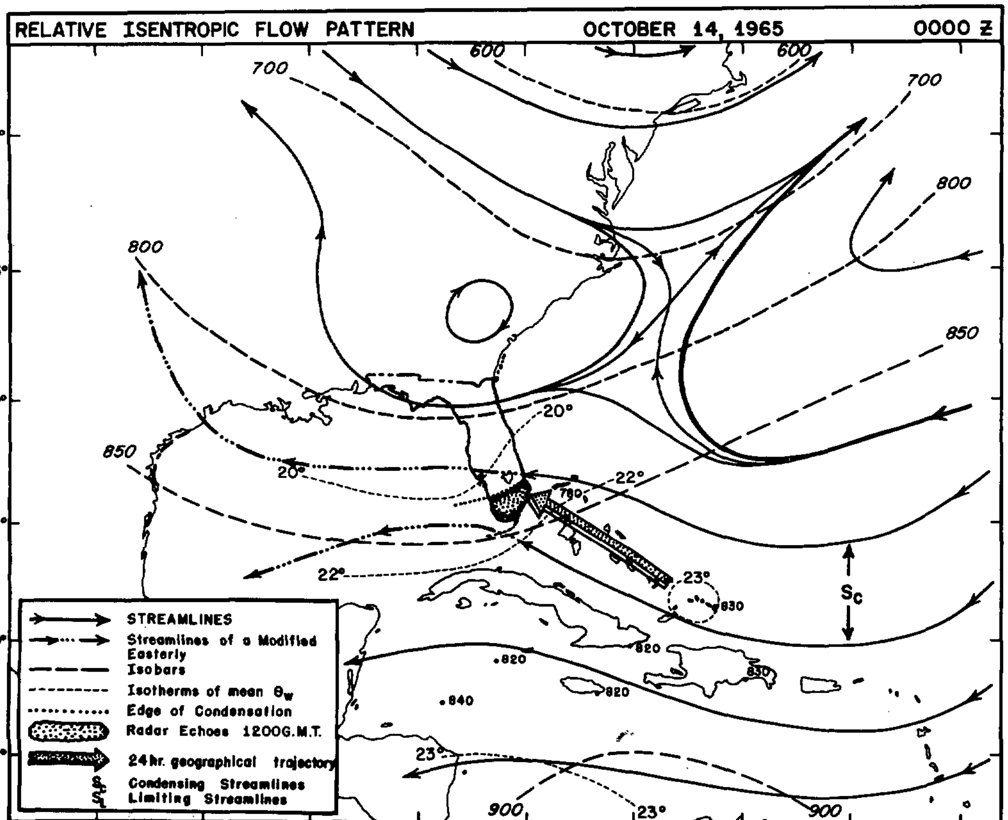

FIGURE 8.—Isentropic relative-flow chart for $\theta=30°$C., 0000 GMT, October 14, 1965, showing streamlines (solid lines) and isobars (dashed lines) labeled in millibars. The small three-digit numbers entered in the Caribbean area are condensation levels in millibars for various stations. Along the set of streamlines labeled S_c condensation should occur upon the air's arrival at a segment of the 830-mb. isobar (thin dotted line) over Florida. Stippled area represents the primary echoes, 1200 GMT, October 14, 1965. Thin dashed lines are isotherms of wet-bulb potential temperature θ_w in °C., averaged over the bottom 100 mb. The stippled arrow is a 24-hr. fixed-coordinate trajectory. (See text.)

3. ISENTROPIC FLOW PATTERNS

The procedure for development of an isentropic steady-state analysis, which can give insight into the vertical and horizontal motions of air parcels, has been described in great detail by Carlson and Ludlam [3] and by Green, Ludlam, and McIlveen [4]. Briefly, the method consists of plotting the isentropic surfaces after selection of suitable values of potential temperature, θ, from a complete set of thermodynamic diagrams. By employing the phase velocity of a suitable and coherent large-scale wave pattern of interest, the winds are corrected to describe the isentropic streamlines relative to the translating pattern. In this case the movement of the large-scale trough-ridge and cloud system, as stated earlier, was about 9 kt. eastward and accordingly this velocity was subtracted from the initial isentropic winds. The patterns generated in this case are very similar to those described in the two articles cited above. In the following sections it will be convenient to refer to the wet-bulb potential temperature, θ_w, and the *saturation* wet-bulb potential temperature, θ_s, defined as the value of θ_w corresponding to the state of saturation at an observed temperature and pressure.

FLOW IN THE LOWER TROPOSPHERE

The relative isentropic streamlines on the 30° C. surface ($\theta=303°$ A.; fig. 8) represent the flow at a level in the upper part of the trade wind moist layer. Condensation levels throughout the Tropics indicate that the air should begin to condense upon being lifted to 830 mb. In particular this means that large-scale condensation on this surface should begin where the flow intersects the 830-mb. isobar across Florida. If we assume that the trade winds have an effective northern limit and that the condensation levels were appreciably higher north of the Bahama Islands, the line segment (shown dotted in fig. 8) corresponding to the upwind edge of the condensation can be drawn realistically to extend across southern Florida to a position somewhat north of the westernmost Bahama Islands, a length of about 200 mi.

FLOW IN THE MIDDLE TROPOSPHERE

On the isentropic chart for 41° C. ($\theta=314°$ A.; fig. 9) the relatively high condensation levels of about 550 mb. (equivalent to θ_w of 17.5° C.) well upstream from southern Florida are observed to lower abruptly to about 620 mb. ($\theta_w=20°$ C.) as the streamlines enter the area occupied by cloud. This rapid increase in the water vapor content of the air aloft represents a turbulent mixing of the air parcels with convective updrafts. In this manner the original flow can be said to have been *modified* by the convection and the degree of modification is readily apparent upon examination of the isentropic charts and individual soundings (see also, for example, the distribution of temperature and vapor content at Miami in fig. 7).

Figure 9 shows that the flow to the right of the streamline, S_L, turns northward and ascends some 40 or 50 mb.

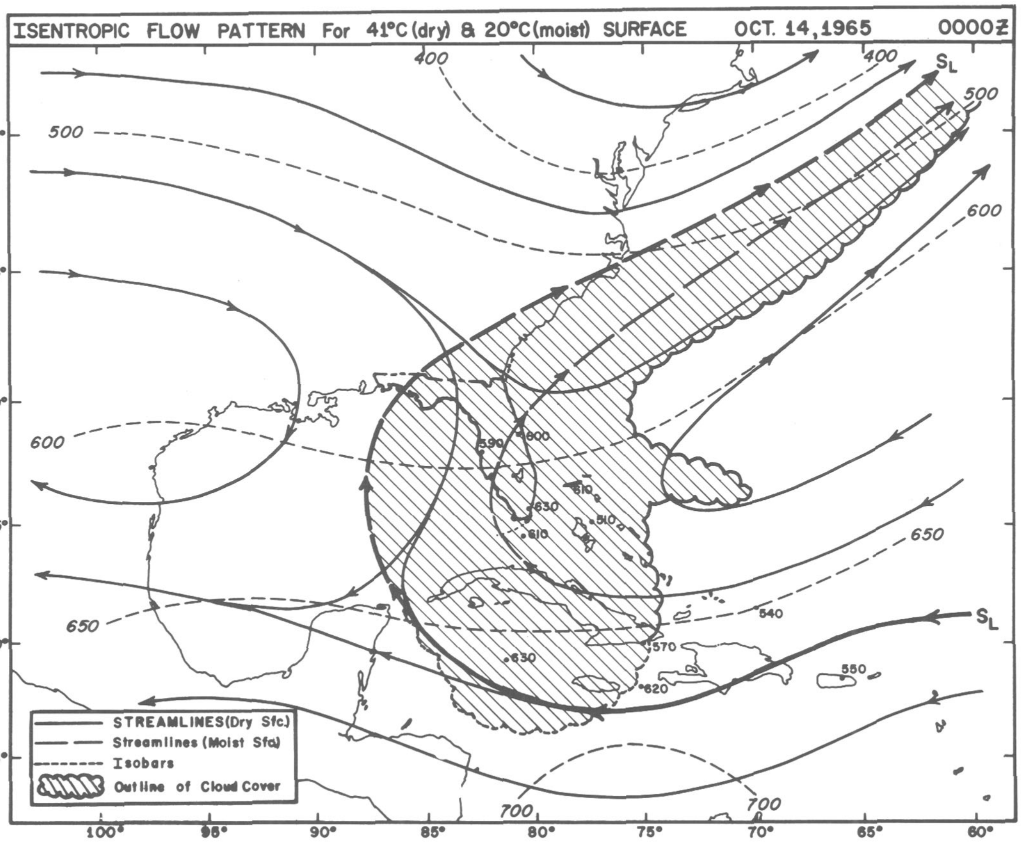

Figure 9.—Isentropic relative-flow pattern for $\theta=41°C.$, 0000 GMT, October 14, 1965, showing streamlines (solid lines) and isobars (dashed lines) labeled in millibars. The small three-digit numbers entered in the Caribbean area are condensation levels in millibars for various stations. Hatching represents the cloud pattern as shown in figure 3, and the dashed arrows are streamlines on the moist surface $\theta_w=20°C.$, which depart from the original dry surface following saturation of the air parcels. The southernmost streamline to turn northward into the frontal zone is labeled S_L.

prior to its arrival in the region of intense convection, where the air in the middle troposphere became rapidly saturated as the result of large-scale lifting in combination with the modification process. Beyond that point the location of the relative streamlines becomes ambiguous. In constructing figure 9 it was assumed that the flow downstream from southern Florida was represented by moist adiabatic motion of a layer of saturated air with θ_w of 20° C. This device permits the construction of the streamlines (dashed) which continue to flow on a southwesterly course into the confluent frontal zone, while ascending more rapidly and steeply than on the original dry adiabatic surface. Turning of the streamlines into the frontal zone, in the sense illustrated by figure 9, is reflected in the cloud streak lines in the satellite photograph of figure 10.

This moist layer is recognizable on the Cape Kennedy sounding (fig. 11) as a rather deep saturated segment above 680 mb. Farther downstream at Jacksonville this air appears to be located above 450 mb. (fig. 12). In the satellite photograph of figure 13, bright latitudinal streaks of cirrus cloud, oriented parallel to the upper tropospheric wind, are visible in the center and right side; to the north can be seen the middle-level cloud which is characteristically of a more dappled appearance. The sharply defined edge to the cloud cover across the Florida panhandle corresponds to a portion of the streamline S_L in figure 9.

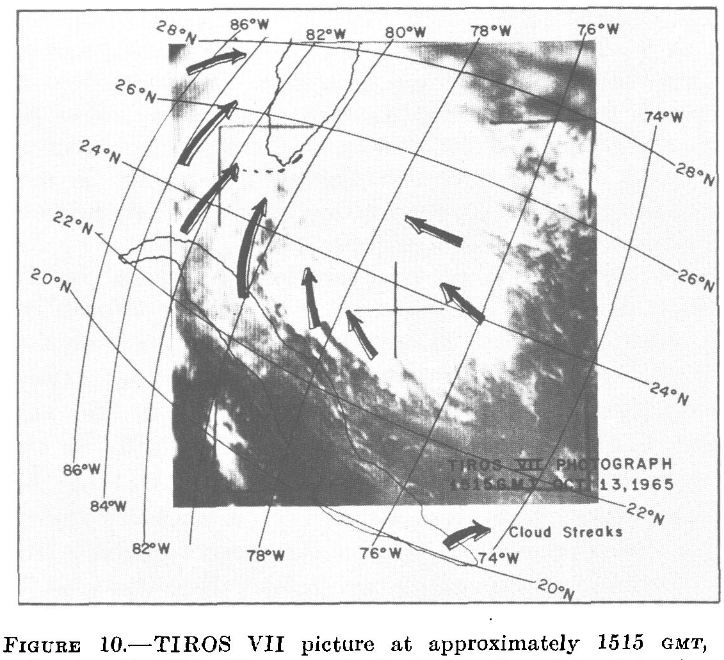

Figure 10.—TIROS VII picture at approximately 1515 GMT, October 13, 1965. The arrows indicate direction of cloud streaks. Florida and Cuba are outlined.

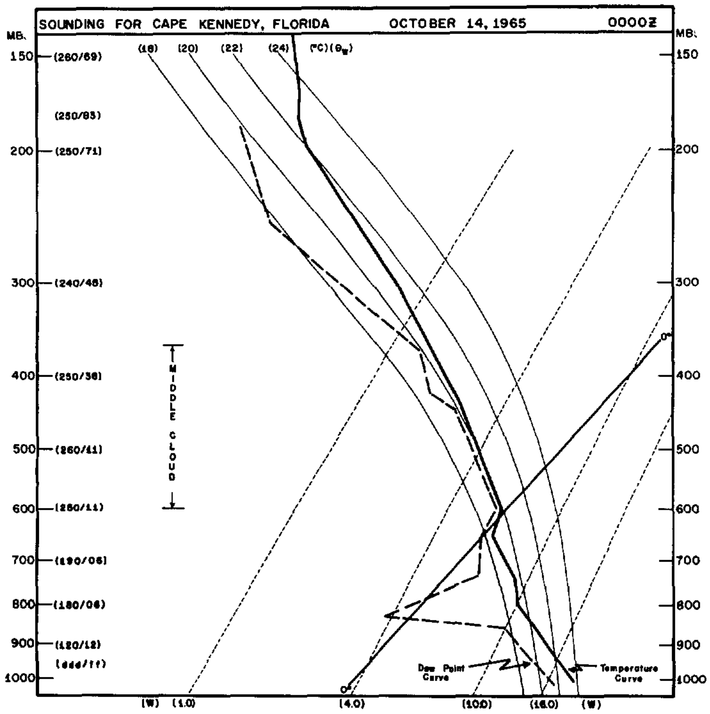

FIGURE 11.—Sounding for Cape Kennedy, Fla., 0000 GMT, October 14, 1965. The bracketed segment labeled MIDDLE CLOUD corresponds to a moist layer within which θ_w was about 20°C. Wind direction and speed in degrees and knots are entered at the far left.

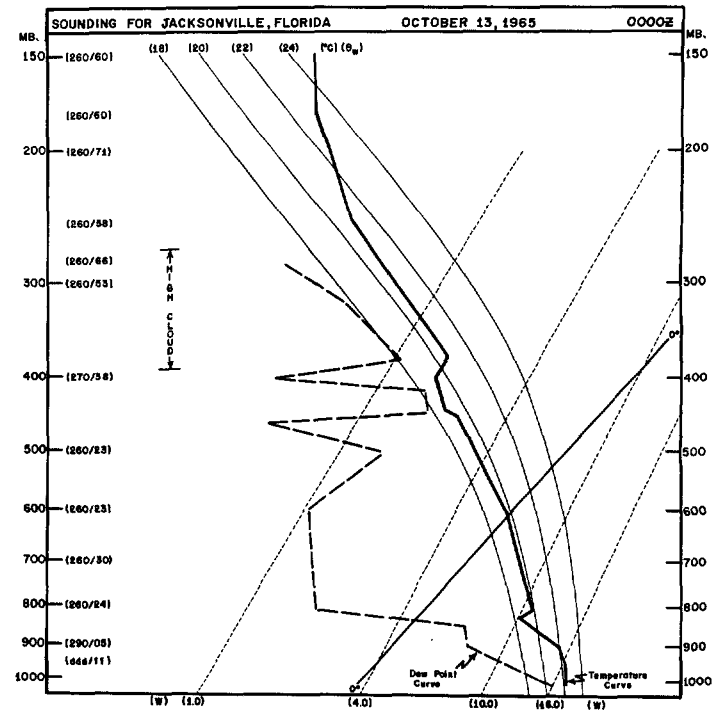

FIGURE 12.—Sounding for Jacksonville, Fla., 0000 GMT, October 13, 1965. The bracketed segment labeled HIGH CLOUD corresponds to a layer of cirrus within which θ_w was about 20°C. Wind direction and speed in degrees and knots are entered at the far left.

4. DISCUSSION

INITIATION OF DEEP CONVECTION

The two isentropic charts (figs. 8 and 9) show that the net vertical displacement that the air experienced in traveling from a point upstream in the undisturbed environment to southern Florida, was about 40–50 mb. both within the upper part of the moist layer and in the initially drier middle troposphere. It can be demonstrated by reference to a mean October sounding for the Caribbean (fig. 14; see also its corresponding abstract in table 1) that, provided the vertical motion is zero near the ground, large-scale lifting will most likely produce condensation first in the upper part of the trade wind moist layer. Further, condensation brought about by lfiting alone is not likely to occur in the middle troposphere at subtropical latitudes, where vertical displacements of 80 mb. or more are necessary to saturate the air. However, lifting of the air by this amount did permit the value of θ_s in the middle levels to fall to about 20° C. in the region where condensation was occurring (see fig. 2). Thus, where θ_w in the condensing air exceeded 20° C. (i.e., below about 750 mb. on the mean sounding), the air became conditionally unstable and there was a widespread growth of convective towers with roots in the middle cloud layer. Although this convection was limited, of necessity, to the middle troposphere by the relatively high values of θ_s in the upper troposphere and by the strong braking action on the convection by the middle-level dryness, some locations were experiencing heavy showers from the high-based convection. It is known (see, for example, Spillane [6], p. 108) that such rainfall can produce a gradual lowering of the cloud base leading eventually to the involvement in the updrafts of air from the lowest and most unstable layers. Hence, the initiation and continuing maintenance of widespread thunderstorms over a given area was favored by large-scale condensation of conditionally unstable air there. In figure 8 there is reasonable agreement between the predicted edge of the condensation (the dotted line) and the shaded region of strong echo activity. (During the writing of this paper the author documented several other instances when altocumuli were widespread over Florida. On a few such occasions radar and visual observations indicated that precipitation was falling from the cloud layer and the base of the cloud was beginning to lower where buildups of convective towers were rising from the altocumulus cloud layer to about 20,000 ft.) More exact agreement in this diagram would have resulted from selection of a condensation level somewhat lower than 830 mb. in the sparse-data region upstream from Florida. Indeed, some indication does exist for believing that the condensation levels were higher over the Bahama Islands than elsewhere in the subtropics (see the following subsection).

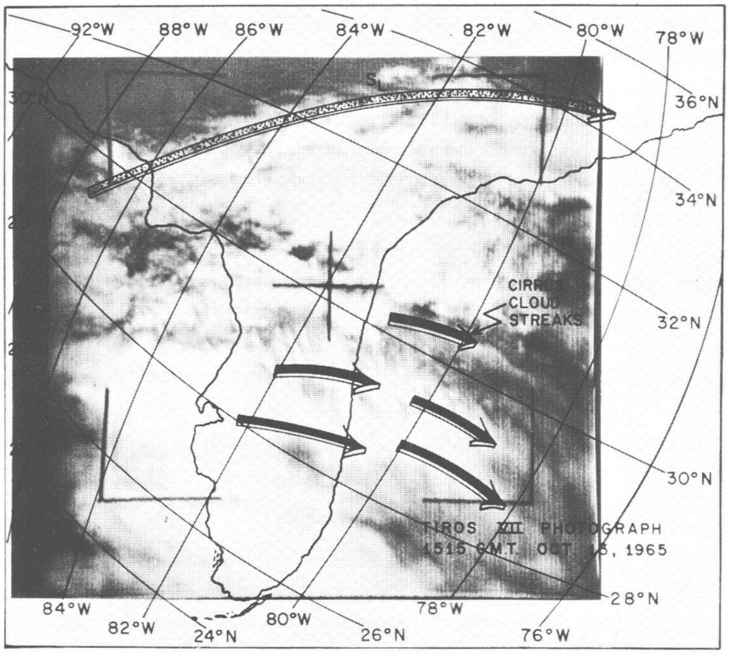

FIGURE 13.—TIROS VII picture at approximately 1515 GMT October 13, 1965, showing latitudinal cirrus streaks (indicated by arrows). The edge of the frontal cloudiness (heavy arrow) suggests the limiting streamline S_L of figure 9.

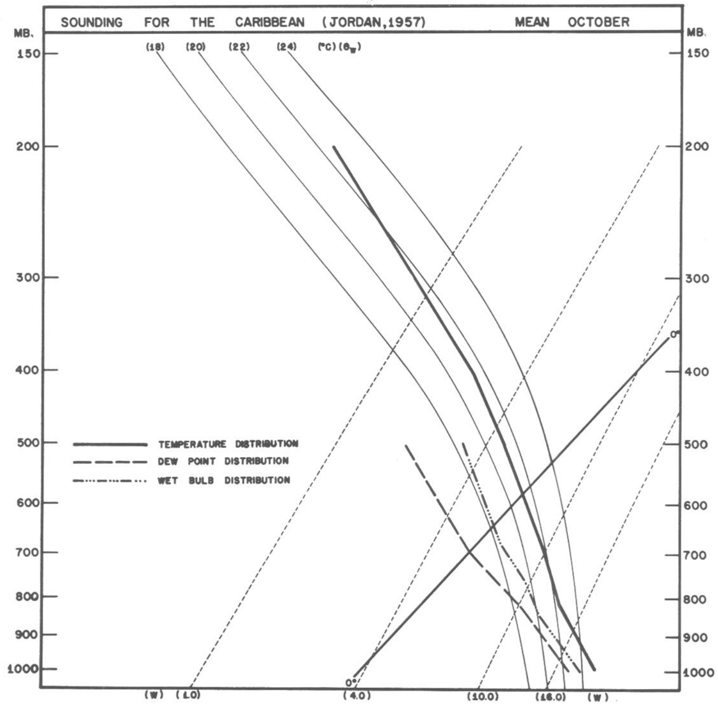

FIGURE 14.—Mean sounding for the Caribbean during October; after Jordan [5]. In addition to the temperature and dew-point curves the distribution of wet-bulb potential temperature (dash-dotted line) is entered on the diagram. Values in table 1 refer to this figure.

HEAVY RAINFALL

According to the U.S. Weather Bureau radar at Miami, the precipitation was falling over or very close to the mainland of Florida during the hour ending at 1200 GMT on the 14th. It was possible with the aid of hourly reporting stations to perform a crude analysis of the rainfall pattern, and by integration to obtain an estimate of the average hourly rainfall. This rate was 3×10^{14} gm./hr.; most of this falling over an area about 200 mi. across. The isentropic chart for the lower troposphere (fig. 8) suggests that all the conditionally unstable air within the part of the flow labeled S_c became involved in the convective updrafts in the vicinity of the dotted line across Florida. If the length of S_c is chosen as 200 mi., the depth of the conditionally unstable air as 250 mb., the relative speed of the flow as 28 kt., and the mean vapor content of the column as 13 gm./kgm., a simple continuity argument leads to an estimate of the water vapor flux of 4×10^{14} gm./hr. Despite reasonable agreement between the inflow of water vapor and the precipitation, the model fails to explain the unusual concentration of very heavy rainfall near Ft. Lauderdale on an even smaller scale than 200 mi. across. One speculation concerning this phenomenon is prompted by the seemingly non-advective increase in θ_w over the lower Bahama chain from the 13th to the 14th (see figs. 4 and 5). A fixed coordinate trajectory, constructed to lead back over a 24-hr. period from the vicinity of Ft. Lauderdale at 0000 GMT, October 14 (fig. 8), suggests that a more unstable type of air was reaching the cumulonimbi from the lower Bahamas on the 14th and 15th.

It is felt that the relatively high concentrations of rainfall along this part of the Florida coastline are the result of a peculiar influence of the local geography upon the flow. This influence may be associated with the Bahama Islands. A striking feature of these islands is that they are marked by a vigorous trade-cumulus convection which is notably more intense than that over the surrounding waters. Moreover, cumulus activity, a manifestation of the local anabatic circulation, is known to be enhanced over elongated islands and to persist in a narrow plume downstream when the surface wind blows parallel to the major axis of the island. (For an example of this effect, see Malkus [7].) Within such a moist plume θ_w is markedly higher (and hence condensation levels are lower)

TABLE 1.—*Values of saturation wet-bulb potential temperature θ_s, wet-bulb potential temperature θ_w, and distance to condensation following a lifted parcel, LC. Brackets refer to averages of quantities taken over layer. All values pertain to Jordan's [5] mean October sounding for the Caribbean. (See fig. 14)*

Level (mb.)		θ_s (° C.)		θ_w (° C.)	LC (mb.)
1000		-----		[23.7	50
900		-----	22.6	21.2]	50
800		22.6		20.0	50
700		22.0		[18.8	60
600		[21.3	18.5	18.1	80
	21.5				
500		21.4		18.5]	80
400		21.5]		-----	-----
300		21.8		-----	-----
200		22.5		-----	-----

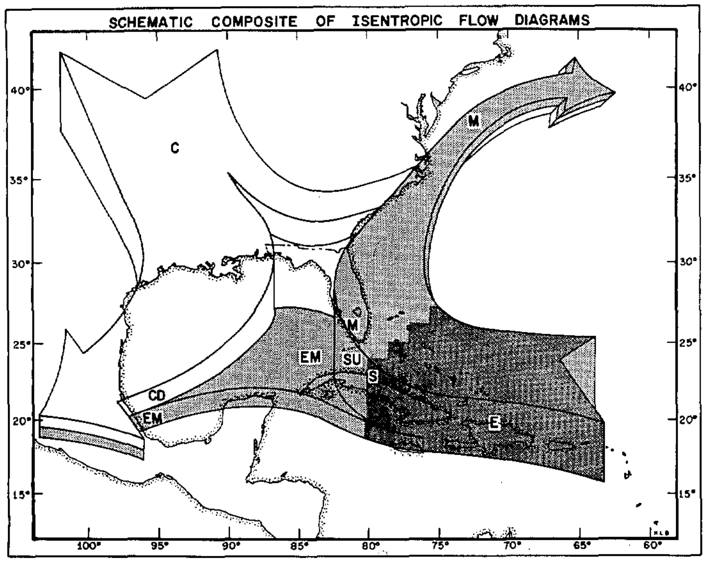

FIGURE 15.—Schematic flow pattern composited from the relative-isentropic flow charts of figures 8 and 9. The basic easterly current E arrives at S where, after some ascent, saturation occurs in the upper part of the moist layer. Conditionally unstable air, condensing at SU, initiates the convection which modifies the temperature and moisture distribution aloft. The modified flow M becomes confluent as it continues to ascend northward into the frontal zone. Near the ground the flow passing through SU is also modified to some extent by the convection and it continues westward as EM to join a stream of potentially cold air C which is descending in the current CD.

than in the surroundings. In the event that the large-scale wind in the moist layer blows parallel to the elongated island chain (an azimuth of 120 deg.) these plumes may align themselves along the flow and form a moist corridor which might become detectable on a synoptic scale.

In a transient system the formation of a moist corridor would be fortuitous and of a passing nature.[1] On the 12th the winds were somewhat north of east over the lower part of the islands but by the 14th the winds there were from the east-southeast at low levels. Although further investigation is necessary to determine the validity and extent of such a moist corridor, its existence would imply that there was a highly favorable zone for the formation of cumulonimbi extending some distance downstream from the westernmost islands.

5. CONCLUSION

The isentropic charts presented here suggest that the heavy rainfall was brought about by the lifting of conditionally unstable layers of air to saturation. Although large-scale convergence is a general prerequisite for the production of heavy rain, the adiabatic ascent in this case appeared to constitute a forcing of the convection over a relatively small and prescribed area. The further concentration of heavy rain on a scale well below that of the isentropic charts may have been due to a local moistening effect upon the flow by the Bahama Island chain in combination with a favorable wind regime.

The composite streamline pattern (fig. 15) also suggests that the rainfall was part of a large-scale pattern in which the condensation and convection at a relatively low latitude occurred in response to the influence of a middle-latitude system. The western Atlantic Ocean is a region notable for having such an influence on the subtropical easterlies (see Riehl [8], p. 227 and Ballenzweig [9], p. 14). It seems quite likely that the passage of the middle-latitude system on this occasion was indirectly responsible for the heavy rain and thus for the formation of the tropical depression described earlier.

[1] The 0000 GMT surface dew points, tabulated for three stations in the upper Bahamas for the months of October, 1963 and 1964, were highest when the surface wind was between azimuths of 090 and 110 deg.

ACKNOWLEDGMENTS

The author would like to express appreciation to Harry F. Hawkins and Banner I. Miller of the National Hurricane Research Laboratory for their helpful criticism of the manuscript. The author was also assisted by R. R. Carrodus of the National Hurricane Research Laboratory who drafted and helped compose the diagrams. Appreciation is due Mrs. Bonnie True for typing the manuscript, and Charles True for making the prints. In numerous small requests for data made by the author, prompt cooperation was received from the National Hurricane Center, Miami, Fla., the National Satellite Laboratory at Suitland, Md., and the National Weather Records Center at Asheville, N.C. Finally, the author is indebted to F. H. Ludlam of the Imperial College, London, England, who inspired many of the basic ideas for this paper.

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[*Received November 17, 1966; revised February 1, 1967*]